The Cessation of Flickering during Dips in Cygnus X-1

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ABSTRACT

We report the discovery of the cessation of flickering in dips in the black hole candidate Cygnus X-1, detected for the first time in the ASCA observation of May 9th., 1995. During this observation, particularly deep dipping took place resulting in strong changes in hardness ratio corresponding to absorption of the power law spectral component. The deadtime corrected light curve with high time resolution clearly shows a dramatic decrease in the extent of flickering in the band 0.7 - 4.0 keV during dipping, but in the band 4.0 - 10.0 keV, there is relatively little change. We show that the rms flickering amplitude in the band 0.7 - 4.0 keV is proportional to the X-ray intensity in this band which changes by a factor of almost three. This is direct evidence that the strong Low State flickering is intrinsic to the power law emission; ie takes place as part of the emission process. The rms amplitude is proportional to the intensity in the low energy band, except for a possible deviation from linearity at the lower intensities. If confirmed, this non-linearity could imply a process such as electron scattering of radiation which will tend to smear out the fluctuations, or a process of fluctuation generation which depends on radial position in the source. Thus timing observations during absorption dips can give information about the source region and may place constraints on its size.

Subject headings: accretion, accretion discs — scattering — (stars:) binaries: close — stars: circumstellar matter — stars: individual (Cygnus X-1) — X-rays: stars

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1. Introduction

Cygnus X-1 is well known as one of the best Galactic black hole candidates, with a mass of the compact object in the range 4.8 - 14.7 $M_{\odot}$ (Herrero et al. 1995). It is highly variable, and on timescales of weeks and years shows at least two luminosity states: a Low State in which it spends most of its time, and a High State with much softer spectrum (see review by Tanaka and Lewin 1995). There can also be transient reductions in X-ray flux lasting several minutes: ie X-ray dips, during which the spectrum hardens, showing that these are due to absorption (Kitamoto et al. 1984). The X-ray spectrum of Cygnus X-1 is complex, consisting in the Low State of a hard, underlying power law, a reflection component (Done et al. 1992), and a soft excess (Bałucińska & Hasinger 1991). It was previously shown that in a *Rosat* observation, kT_{bb} for the soft excess agreed well with the characteristic temperature of the inner accretion disc for the low luminosity state of the source, indicating that the soft excess was disc emission (Bałucińska-Church et al. 1995). The source also shows rapid time variations on timescales from milliseconds to 10 s of seconds. This rapid aperiodic variability, often called flickering, was discovered in Cygnus X-1 by Oda et al. (1971). Since then there have been extensive studies of such variability in various black hole candidates, and it is generally accepted that the flickering phenomenon originates in the neighborhood of the inner accretion disc although the mechanism is not clear. The strength of variability may be quantified in terms of the *fractional rms amplitude* σ/I_x, and values of 30% - 50% are typical of the Low State of Cygnus X-1 (Belloni & Hasinger 1990). The evidence is that this strong variability arises in the hard power law spectral component that dominates the Low State of the source, whereas the soft spectral component that dominates the High State shows little variability (van der Klis 1995). In Cygnus X-1, previously no major variation of the flickering has been detected during a particular observation. This *Letter* contains results of a 13 hr continuous observation of Cygnus X-1 by ASCA during which strong dipping took place, and we show that the amplitude of flickering decreased dramatically in dips.

2. Results

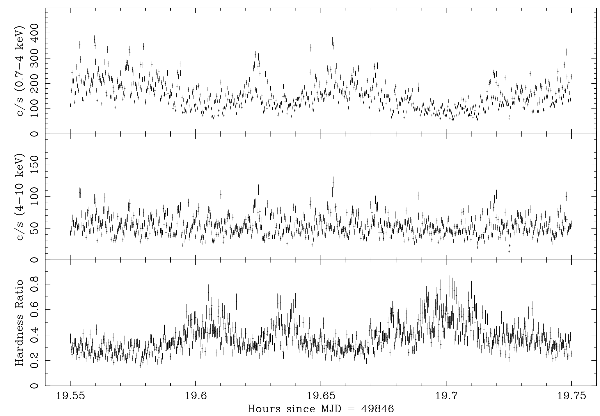

Fig. 1.— GIS light curves in 1 s timebins for the ASCA observation of Cyg X-1 of 1995 May 5th in two energy band: 0.7 - 4.0 keV and 4.0 - 10.0 keV, together with the hardness ratio formed by dividing the light curves.

2.1. Spectral Analysis of Dip Evolution

The observation was made on 1995, May 5th. by the satellite ASCA (Tanaka et al. 1994). Data were collected with the GIS detectors (Ohashi et al. 1996) and the SIS detectors, although only GIS data are discussed here. At $\sim 19^{\rm h}$ UT dipping took place lasting approximately 40 minutes. The deadtime corrected light curve of the strongest dips are shown in Fig.1 in an expanded view with 1s binning. The details of the dip light curves are given in two bands: 0.7 – 4.0 keV and 4.0 – 10.0 keV, together with the hardness ratio (HR) formed by dividing these.

Three dips can be seen lasting 2 to 3 min in each of which there is a strong increase in hardness ratio associated with the photoelectric absorption taking place. We have analysed the spectral changes in dipping by dividing the data into 7 intensity bands including non-dip emission, selected in a time interval including the strong 3rd dip in Fig. 1, and non-dip data on each side of the dip. Spectral analysis of the intensity-selected spectra in the band 0.7 – 4.0 keV were carried out using a blackbody to represent the soft excess, and a power law to represent the hard component, since in this band the reflection component makes little contribution. Using the non-dip data, it was found that the value of the blackbody temperature of the soft excess was well constrained, with $kT_{bb} = 0.13 \pm 0.01$ keV (Bałucińska-Church et al. 1996). The dip data re-

quired a model in which partial covering of the power law took place. Dipping was seen to be due primarily to absorption of the major power law component with N_H increasing from $8.9^{+18.5}_{-0.8} \cdot 10^{21}$ H atom cm^{-2} in non-dip to $72^{+11}_{-9} \cdot 10^{21}$ H atom cm^{-2} in the deepest part of dipping, when the partial covering fraction was $\sim 70\%$. We were not able to constrain very well possible changes in absorption of the blackbody taking place at energies below the ASCA band.

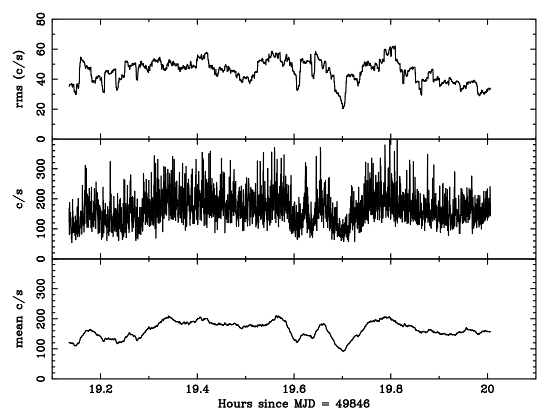

Fig. 2.— (a) rms flickering amplitude evaluated in an 85 s timebin running through the observation; (b) the unsmoothed X-ray light curve in the band 0.7 - 4.0 keV; (c) running 85 s means of the light curve.

2.2. Phase of Dipping

The value of phase that we calculated for the observed dipping using the ephemeris of Gies & Bolton (1982) was 0.70 ±0.02.

Dipping has previously been seen at around phase zero, consistent with inferior conjunction with the Companion. However we cannot be definite about the actual phase because of the errors involved in extrapolating this ephemeris to the date of the observation. This is especially the case because of the possibility that the orbital period is changing, as suggested by Ninkov et al. (1987) based on analysis of all data available at that time. This will not be resolved until there is a new determination of the ephemeris. It is important to decide this point, since dipping at phase ~0.7 would imply absorption in the stellar wind of the Companion.

2.3. Cessation of Flickering

The striking effect that flickering essentially stops in the deepest part of the dipping, is obvious in Fig. 1, particularly in the 3rd dip which is the strongest. In the lower energy band 0.7 - 4.0 keV, it can be seen that flickering on timescales longer than the 1 s binning has an amplitude of 200 c/s in non-dip emission, i.e. the soft X-ray intensity rises from 200 – 400 c/s. However, in dipping it can be seen that this amplitude decreases considerably. The effect is less obvious in the higher energy band 4.0 - 10.0 keV, although there may be some small decrease in amplitude at the third dip.

We have also plotted the data as a function of time in the observation by evaluating the rms amplitude of the variability in 1 s bins in a running 85 s section of data, and also evaluating a running mean of the intensity in these 85 s sections. This is shown in Fig. 2 for the lower energy band 0.7 - 4.0 keV. The middle panel shows the unintegrated light curve with 1 s binning, and the lower panel shows the integrated average values in 85 s timebins. There is some underestimation of the depth of dipping in the averaged light curve, and also of the depth of dipping in the rms amplitude plot as a result of smoothing over a long timebin. However it is clear that there is a good correspondence between amplitude and intensity.

To demonstrate the effect more clearly, the data are replotted in Fig. 3a and 3b. In Fig. 3a the X-ray intensities in the soft band and the hard band are plotted against hardness ratio, so that dipping corresponds to the high values of hardness ratio. It is clear that the peak-to-peak variation in the X-ray intensity falls sharply as dipping takes place. This is shown more clearly in Fig. 3b in which the rms amplitude of intensity variation is plotted against hardness ratio for the two energy bands. This was produced by evaluating the rms deviation of the variability of the data selected within a narrow band of hardness ratio. Firstly, it can be seen that the non-dip value of the amplitude of 60 c/s with a non-dip count rate of 200 c/s in the low band gives a fractional rms amplitude of 30% which is quite typical for the Low State of Cygnus X-1. There is a strong decrease of the amplitude at low energy, but with little change at high energies. To show this more clearly, we plot rms amplitude against X-ray intensity for the two energy bands in Fig. 4. Poisson noise is subtracted from the rms, and also an approximate correction to the intensity is made for the dust-scattered halo in

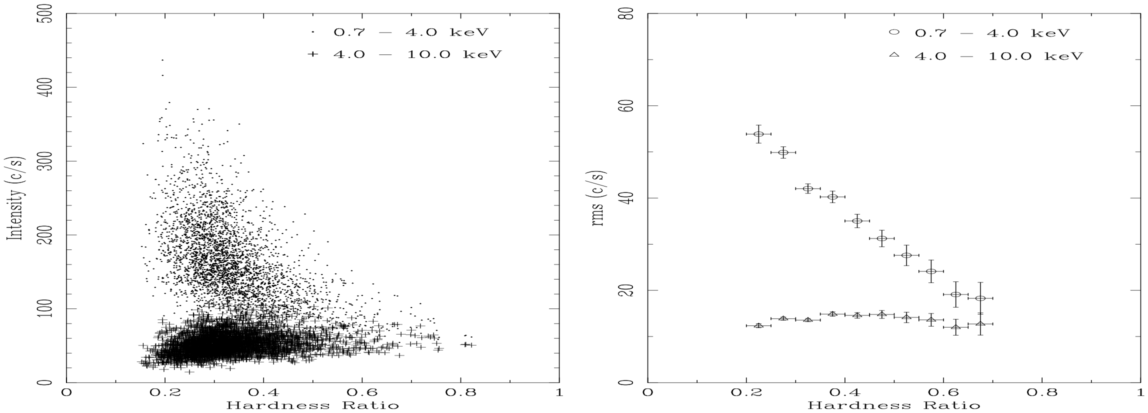

Fig. 3.— (a) Intensity versus hardness ratio in the same two energy bands as in Fig. 1, and (b) rms flickering amplitude in c/s versus hardness ratio.

the band 0.7 - 4.0 keV based on the work of Predehl and Schmitt (1995). The scattered component is not expected to show flickering as this will be smoothed out by the variable time delays. We estimate that the contribution to the intensity of the non-flickering component in this energy band is $\sim 6\%$. The data in the low band are generally consistent with a simple relationship between the variability and intensity which changes by almost a factor of 3 due to photoelectric absorption. However, the points at lowest dip intensity fall below a linear relationship, and in terms of the $1\,\sigma$ errors plotted, the lowest 2 points are an average of $1.8\,\sigma$ below the straight line. Thus the presence of a departure from linearity is likely, but not proven. In the high energy band the amplitude remains constant and there is little change in intensity since the increase in N_H in the dip has little effect in this band.

Thus, the reduction in rms amplitude simply reflects the decreasing power law intensity in the dips due to photoelectric absorption which is strong in the low energy band, but has little effect in the high band. Furthermore, if in the band 0.7 - 4.0 keV, the rms amplitude is divided by the intensity, the fractional rms amplitude is approximately constant, as expected from the approximate linearity of Fig. 4a, indicating the simple relation between amplitude and intensity.

3. Discussion

We have demonstrated for the first time the cessation of flickering during deep dipping in Cyg X-1. The fractional rms amplitude of the variability is about 30% in the non-dip emission, a typical value for the Low State. In the energy band 0.7 – 4.0 keV, there are two spectral components: the soft excess blackbody and the power law. Taking typical parameters for the soft excess, as determined from ASCA and *Rosat* (Bałucińska-Church et al. 1995), we can estimate that this contributes only 8% of the count rate in the band 0.7 - 4.0 keV. Thus it is clear that the power law *must* be involved in the variability, and the linearity implies that the variability originates in the power law emission region, not external to this.

Secondly, we have shown that the change in the strength of variability is simply related to the total intensity (dominated by the power law component) which changes by almost a factor of three in the energy band 0.7 - 4.0 keV due to photoelectric absorption. This is consistent with the simple expectation that, if the intensity falls by a given factor due to photoelectric absorption, then absorption will reduce the variability by the same factor. The departure from linearity in Fig. 4, if substantiated, may reveal futher information about the source, and so we discuss below possible reasons for this non-linearity. Firstly, we have not attempted to correct the data for the contribution to the flickering or to the intensity of the soft excess. The flickering in this component may well be very much less than in the power law. However, because the soft excess, with $kT_{bb} = 0.13$ keV, contributes only at the lowest energies in the ASCA band (below 1.5 keV), it will be totally removed by absorption at an early stage of dipping. Thus, at to-

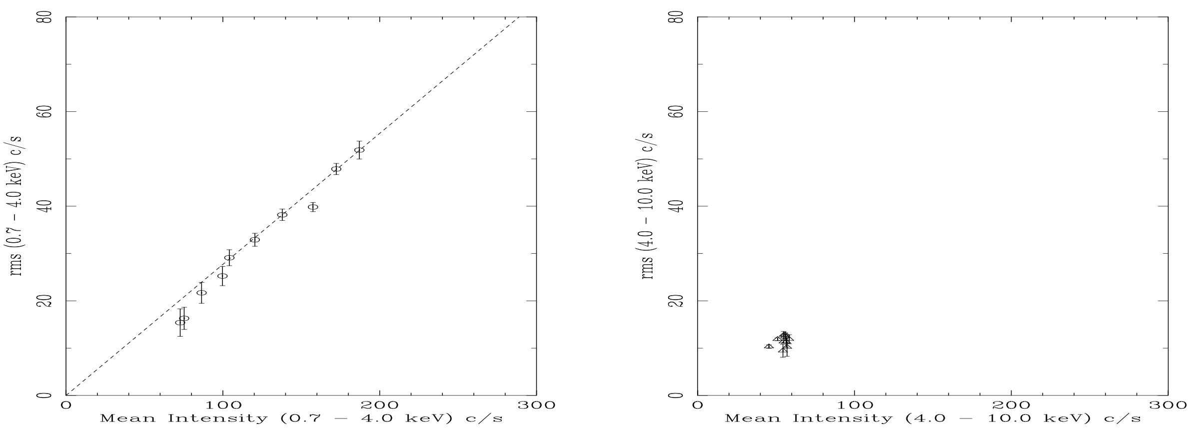

Fig. 4.— Rms amplitude versus x-ray intensity (a) in the band 0.7 - 4.0 keV and (b) in the band 4.0 - 10.0 keV.

tal intensities below 150 c/s in Fig. 4, only the power law component remains, and the plot becomes a plot of power law rms *versus* power law intensity, and so the curvature below 100 c/s is unlikely to be related to the soft excess spectral component. This depends only on the reasonable assumption that this component originates in the central part of the source and so is covered by the absorber during dipping. There are however, effects which can lead to curvature in the plot at low values of intensity. Firstly, the geometry of the absorber causing the absorption dip may be such as to cover the central part of the emission regions only, as suggested by our result that the partial covering fraction rises to only 70% in the deepest parts of dips. If the process generating the flickering were to fall off with distance from the center of the emission region, then the uncovered part of the emission will have reduced flickering in dipping, leading to curvature in the plot.

Secondly, electron scattering close to the source region could produce an effect. If part of the power law X-ray emission gets scattered, then the fast variability will tend to get smeared out. In 1 s timebins, we are determining the rms of longer-lasting shots more than ~ 200 ms in length, although the exact timescale depends on the shot profile. Kitamoto et al. (1984) argued from the timescales of ingress to and egress from dipping in high time resolution TENMA observations, that the major source region was smaller than $4 \cdot 10^8$ cm. Scattering in this region would introduce a variable delay of up to 13 ms which would cause some reduction of flickering in the scattered component for the longer shots. However a region of size $4 \cdot 10^8$ cm is very small in comparison with typical sizes of accretion disk coronae, for example, and if the scattering region was only as large as $4 \cdot 10^9$ cm, there would be a delay of 130 ms which would cause a major reduction of flickering in the scattered component. Then, as the source is only 70% covered in deep dipping, this component would not be completely absorbed but would have reduced variability, leading to curvature in the plot of rms *versus* intensity.

Analysis of the present data constitutes only a first attempt at investigating the results of absorption on the fast aperiodic variability. In principle, this can provide information on the origins of the variability, on the relation between the spectral components and the variability, on the extent to which the source is covered by the absorber, and on possible effects such as electron scattering. Further more detailed work may resolve some of these aspects.

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